QuIPS:
Quantum Invisible Particle Sensor

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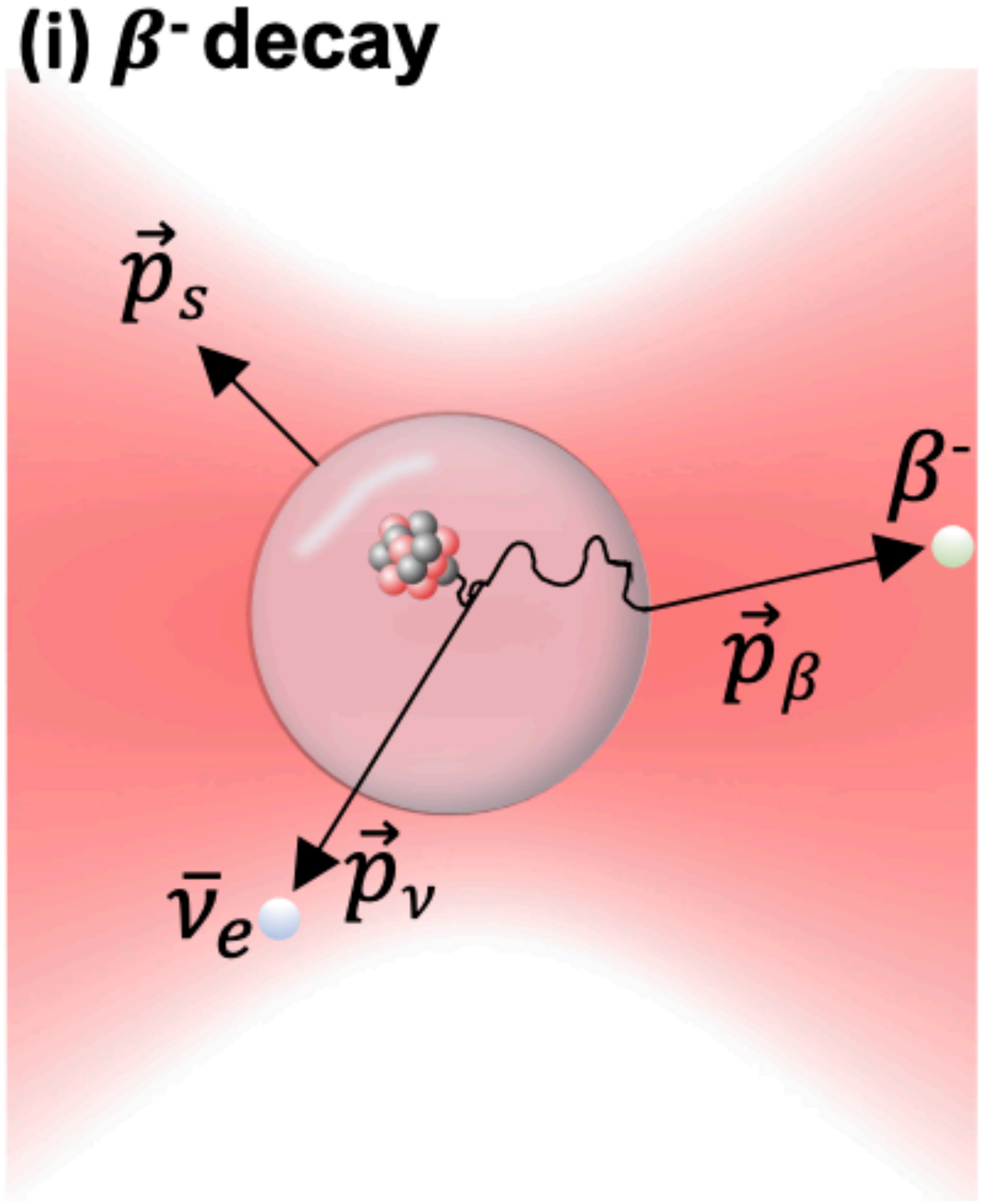
LBNL ATLAS Instrumentation Meeting
May 3rd, 2024

Intro: concept and purpose



- Search for invisible decay products in weak nuclear decays
  - Embed radioisotopes in solid spheres
  - The invisible products can be fully reconstructed through measuring the sphere recoil and the visible decay products

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu}_e $$

$$ \begin{pmatrix} E_s \\ \mathbf{p}_s \end{pmatrix} = \begin{pmatrix} E_{s'} \\ \mathbf{p}_{s'} \end{pmatrix} + \begin{pmatrix} E_i \\ \mathbf{p}_i \end{pmatrix} + \begin{pmatrix} E_{B',i} \\ \mathbf{p}_{B',i} \end{pmatrix} $$

visible products (e-) via pixelated detector

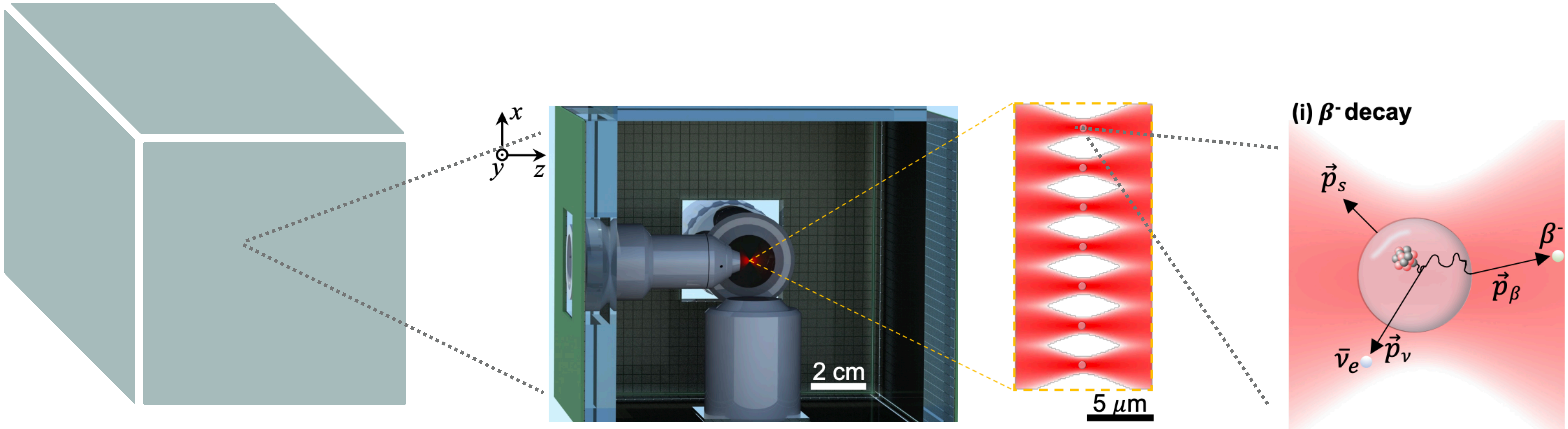
sphere recoil through **quantum** sensor

invisible products
target: heavy sterile neutrinos;
can be altered for wider use

Intro: architecture

electron detector @ LBNL;
this talk

optical trap
parallel work @ Yale



pixelated detector to capture the emitted electron and measure its energy and angle

optical readout to measure the sphere recoil momentum

optical tweezer that levitates the sphere

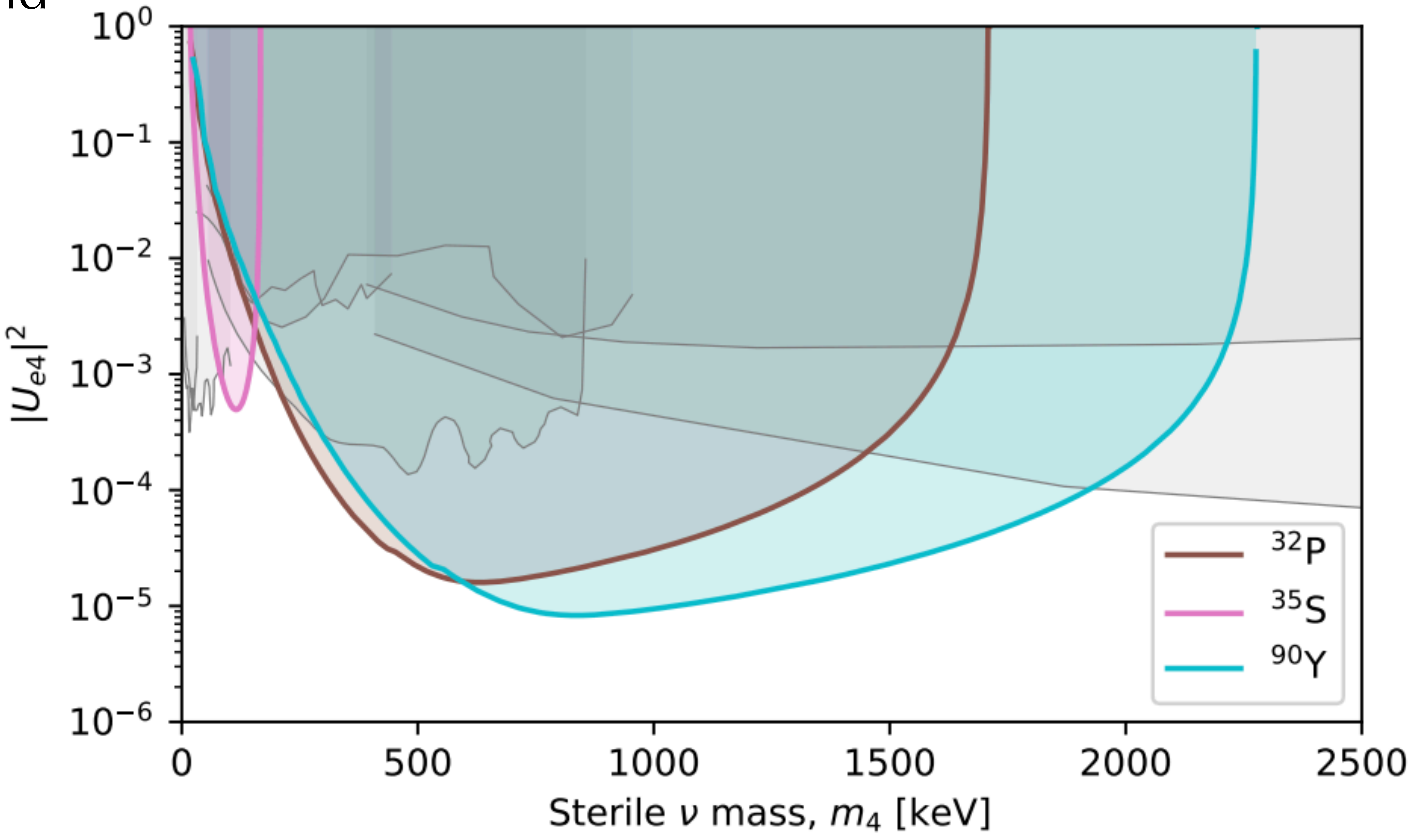
silica sphere with radioisotopes embedded

Intro: the scales and phase space we are talking about

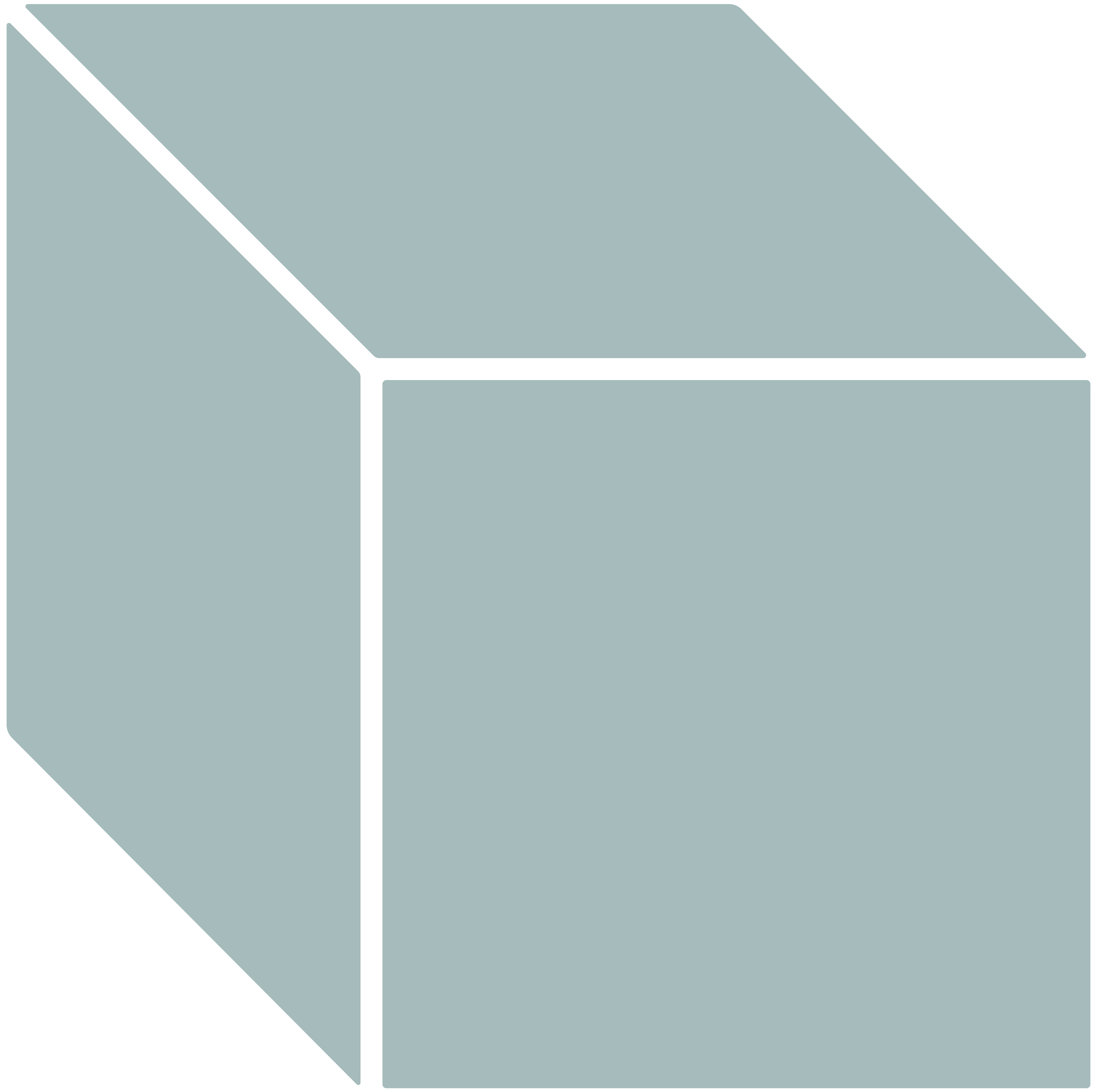
- Target Q~MeV, i.e., keV-MeV electrons and neutrinos
- Sphere recoil momentum
  - ~50nm-1um silica
  - ~femtogram mass
  - ~1% mass-loaded with radioisotope
  - ~100kHz measurement frequency

-> p resolution $\Delta p_{\mathrm{SQL}} = \sqrt{\hbar m_s \omega_s}$ = ~ 15 keV

- Electron detector size ~mm to cm
  - depending on detector type choice
  - comparable resolution



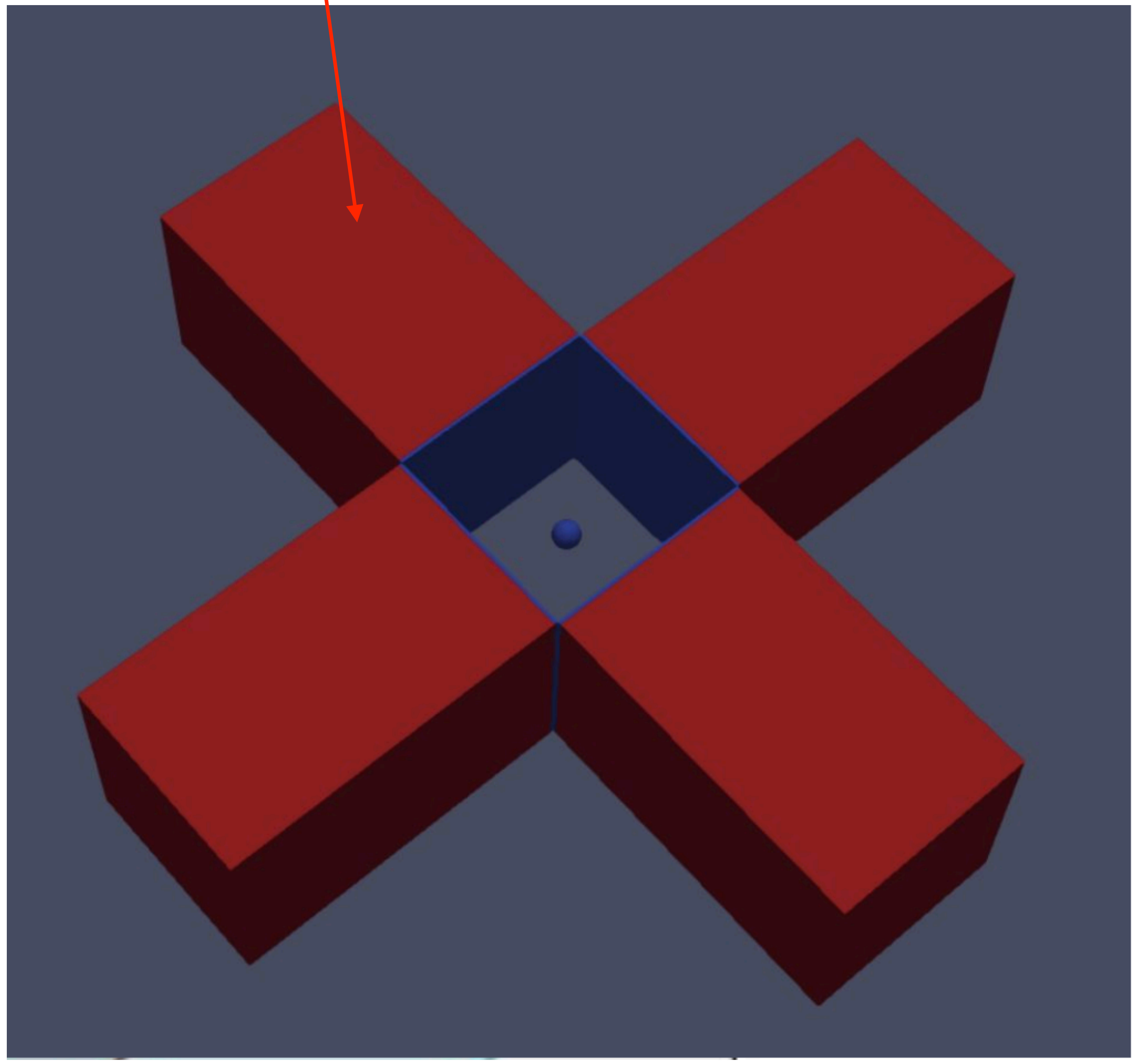
Electron Detector



All we need is high precision energy and angle (position) measurements

Electron Detector: CCD

4 CCD detectors to make a hermetic geometry



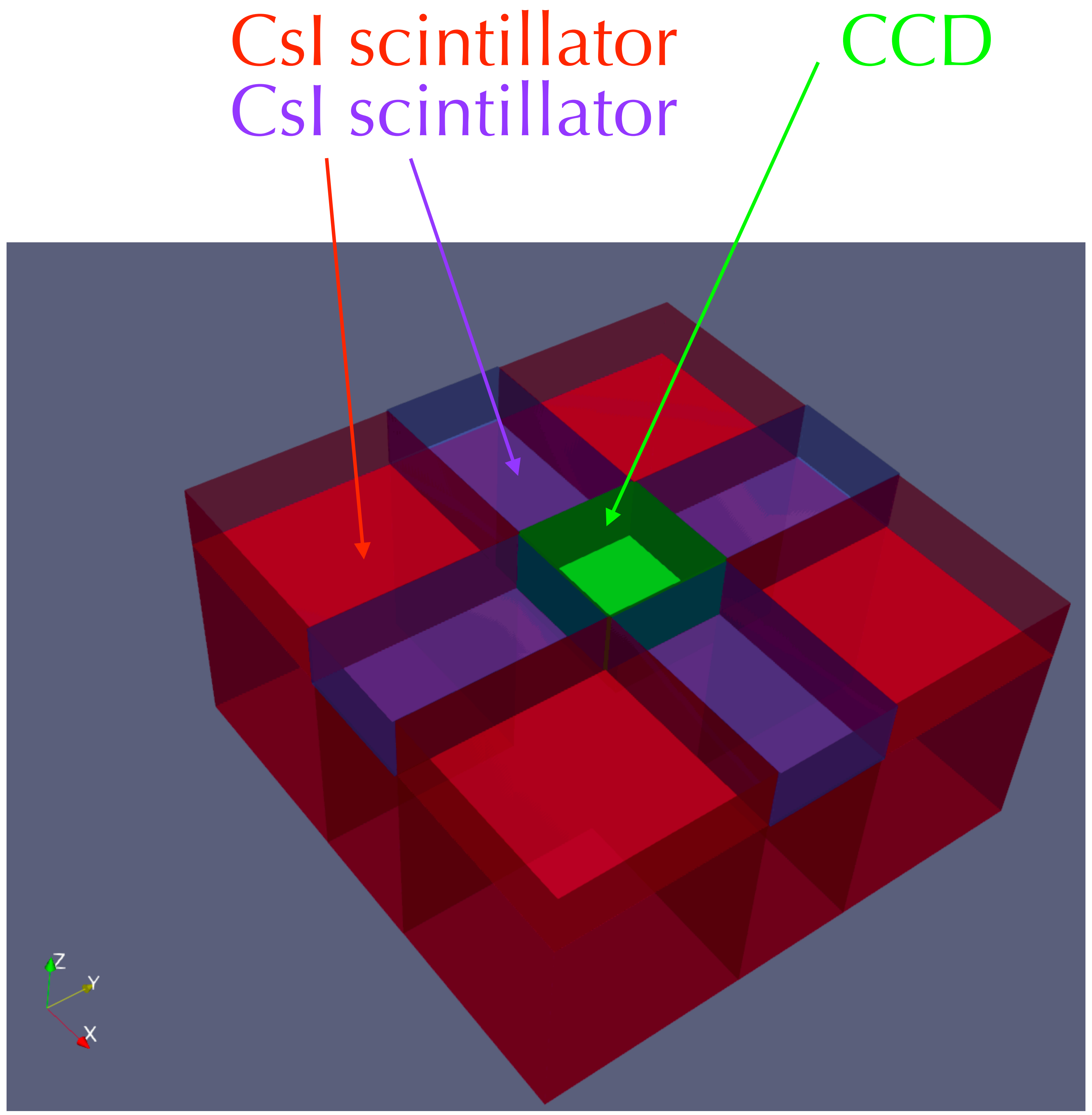
- Primary choice: CCD
  - Fully depleted
  - Good spatial resolution
  - Good energy resolution
  - Potentially fully stop electrons
  - Make use of existing CCD development @ LBNL
    - ~300um depth VFCDD original designed for DESI(P. Denes)

—> CCD detector for both energy and angle measurement

- However…
  - Simulations show many electrons from Q~MeV beta decay pass through ~300um CCD

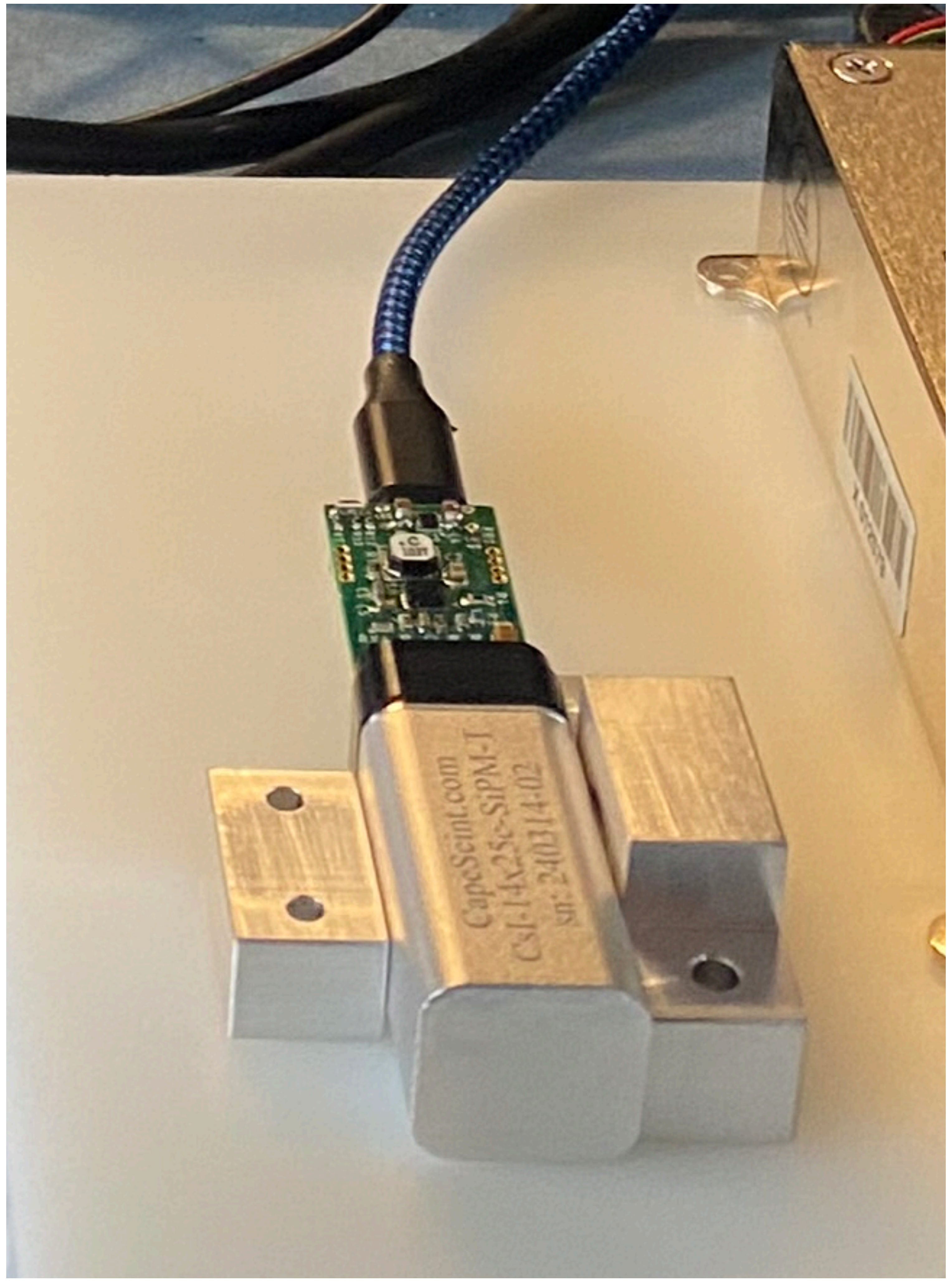
—> can not fully stop —> need back scintillator for energy measurements

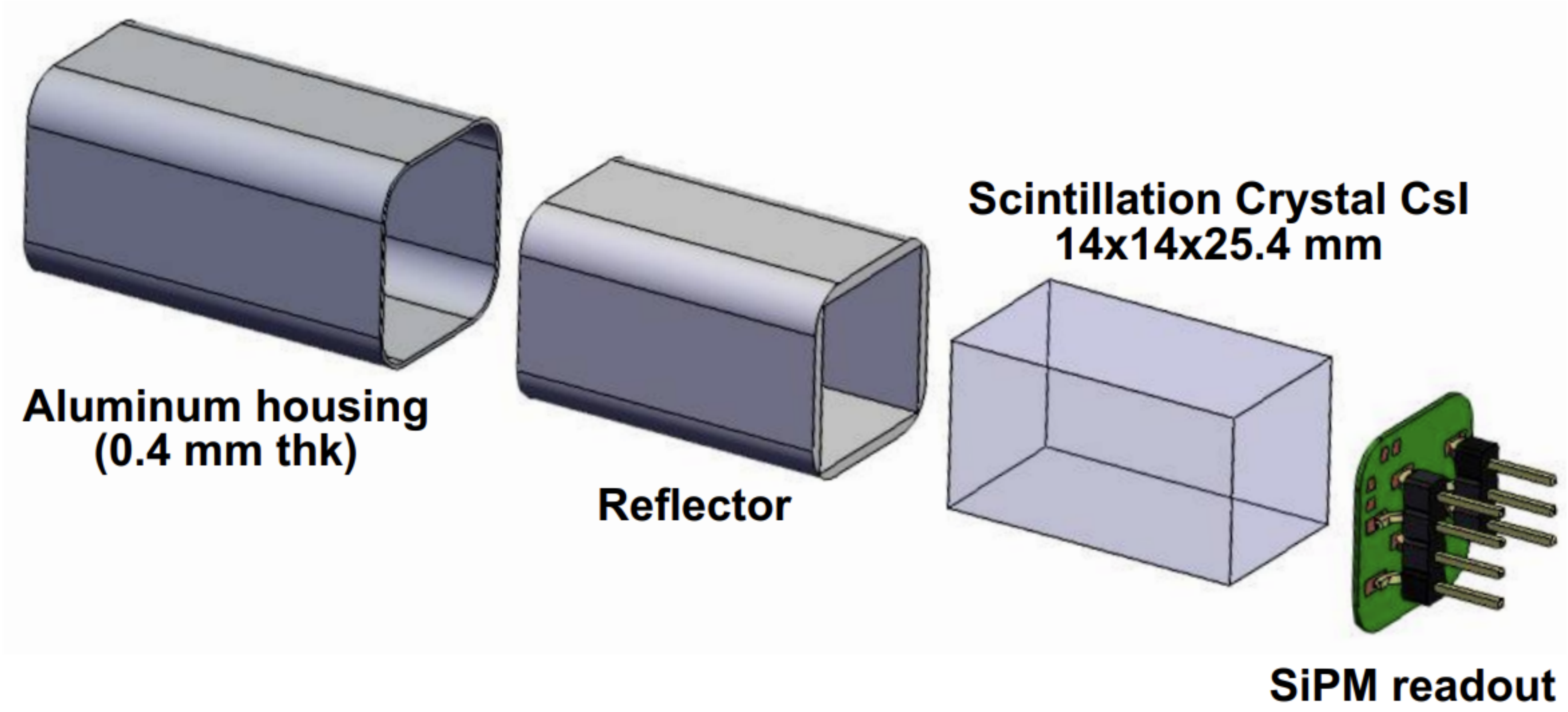
Electron Detector: CCD pixel + CsI scintillator



- CCD pixel (~50um) for angle (position) measurements
  - Also used for triggering
- CsI scintillator (~cm) for energy measurements
  - Geometry revised to make it hermetic
  - CsI scintillator energy resolution is crucial

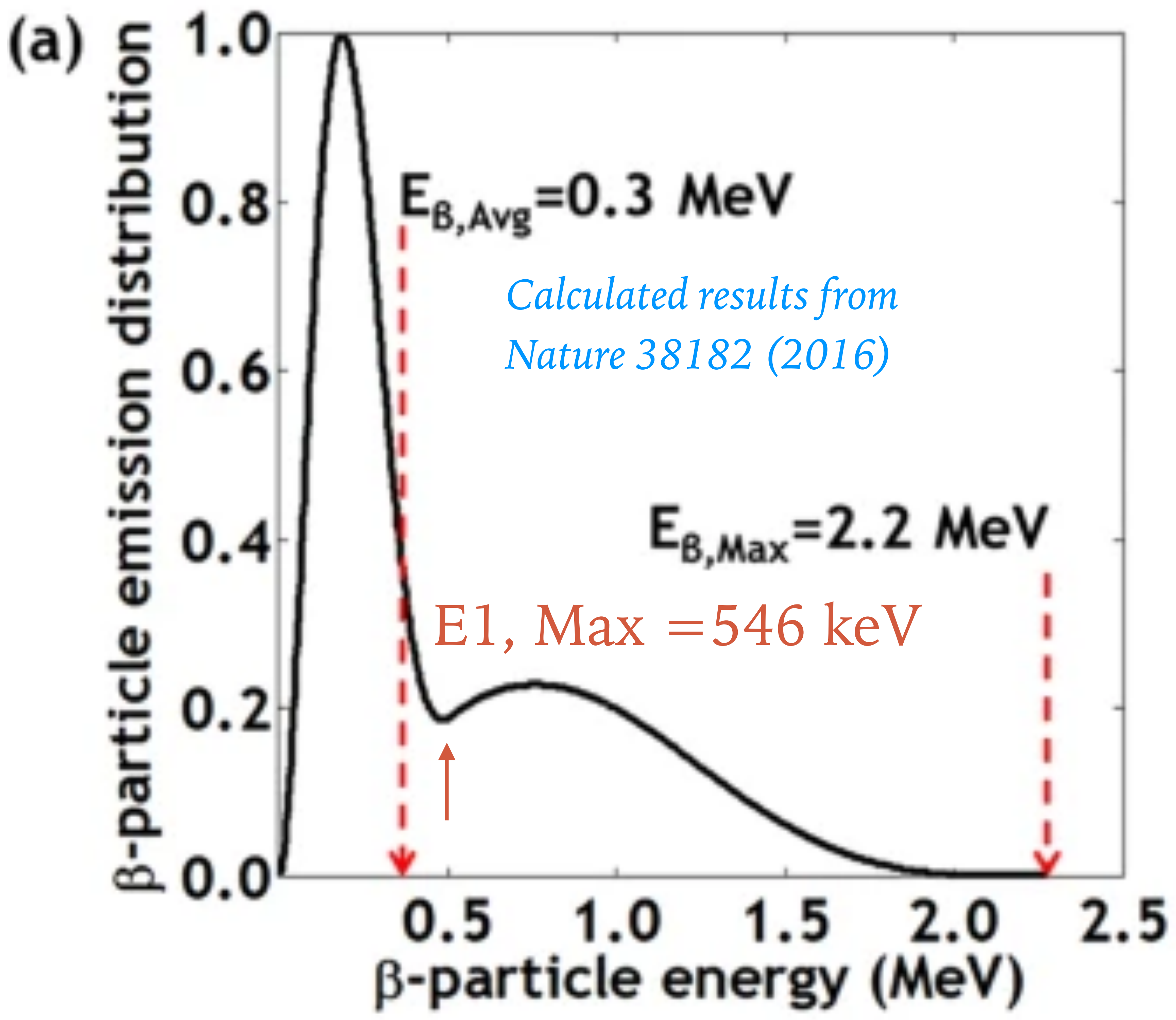
CsI scintillator performance study

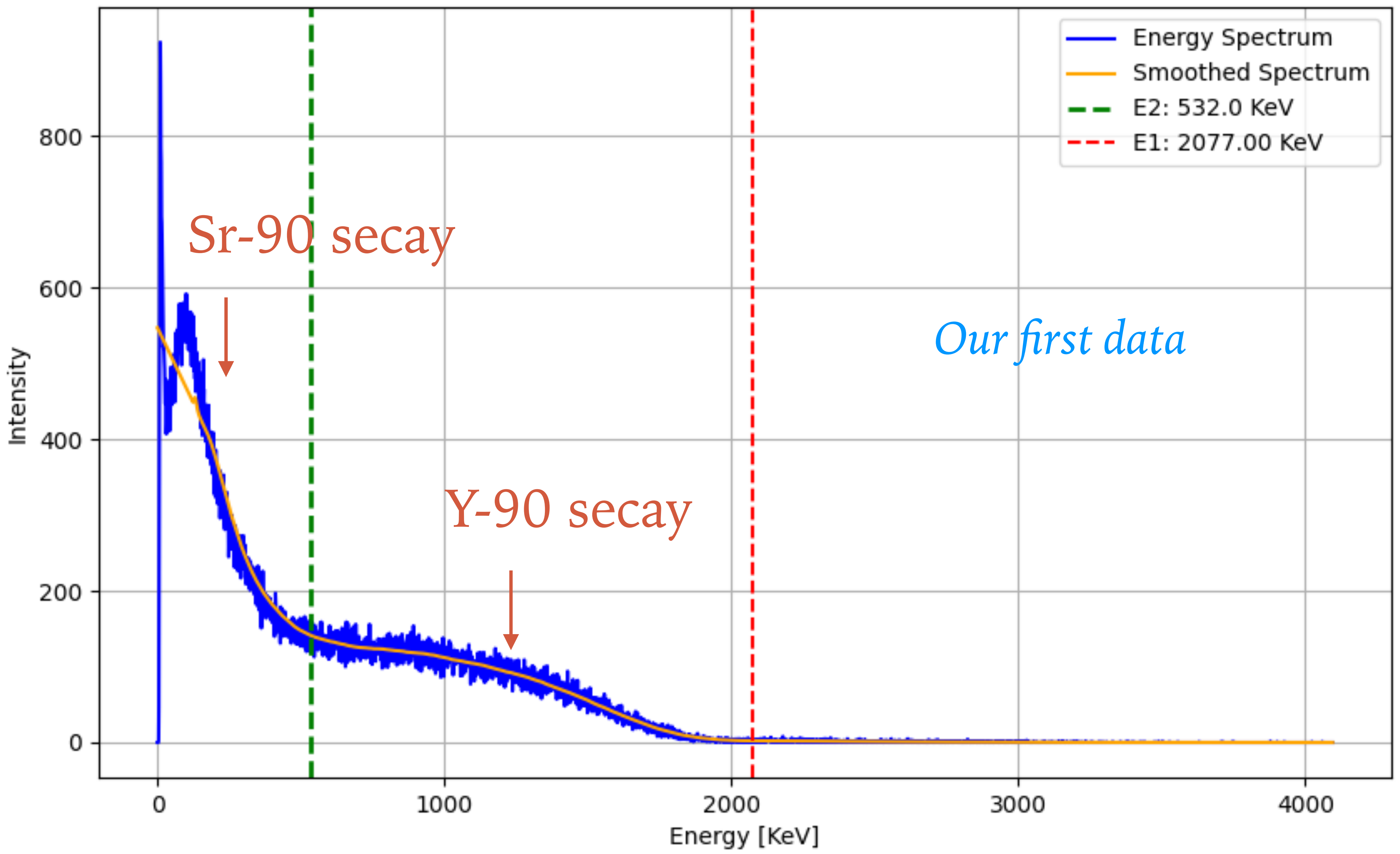




- Prototype Scintillator arrived
  - Came as one integrated piece
- Preliminary test with a Sr-90 gun
  - Its decay daughter Y-90 is what we intend to embed in the spheres

CsI scintillator performance study





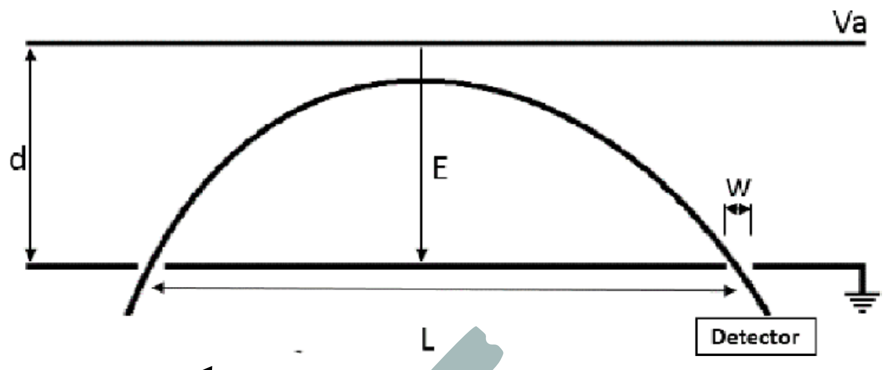
$$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + \beta^- + \bar{\nu} + E_{\beta,Sr}$$

$$^{90}_{39}Y \rightarrow ^{90}_{40}Zr + \beta^- + \bar{\nu} + E_{\beta,Y}$$

- Spectrum roughly agrees with expectation
- For more precision calibration and performance study, need mono-energetic source

CsI scintillator performance study: monochromatic beta source

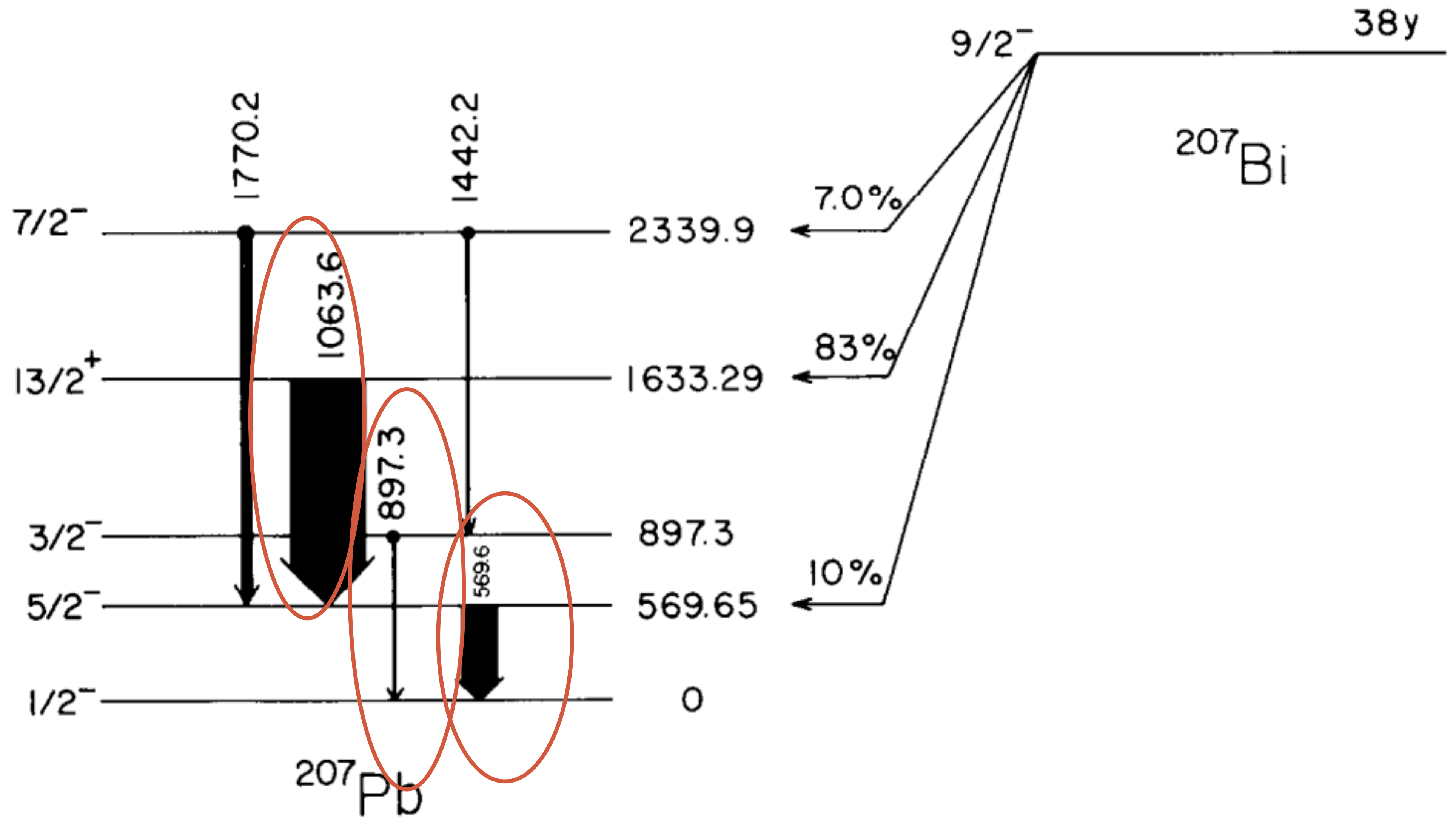
- Electron energy selector
  - Table-top accelerator ✗
  - Filter with parallel plates (electric filed)

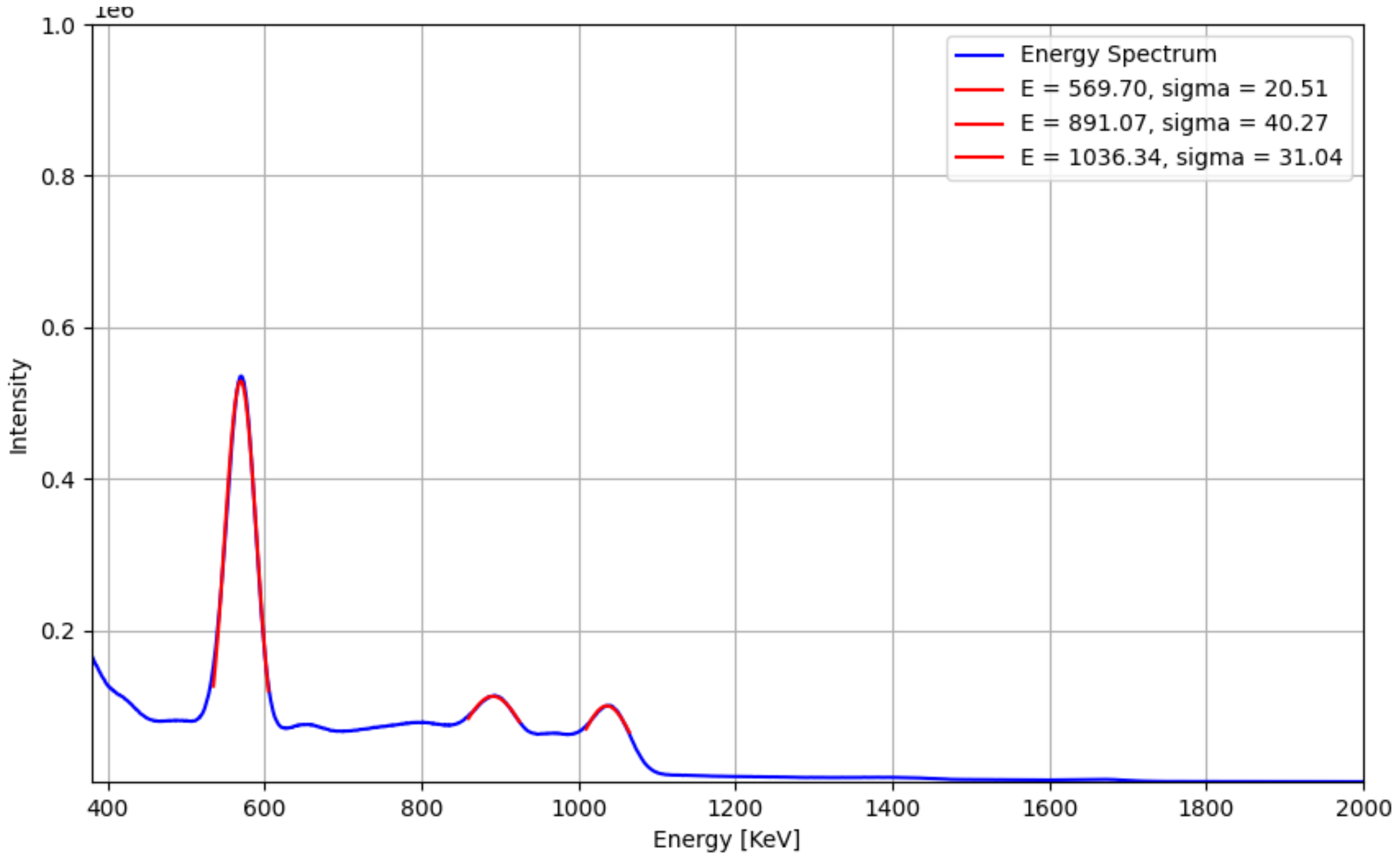


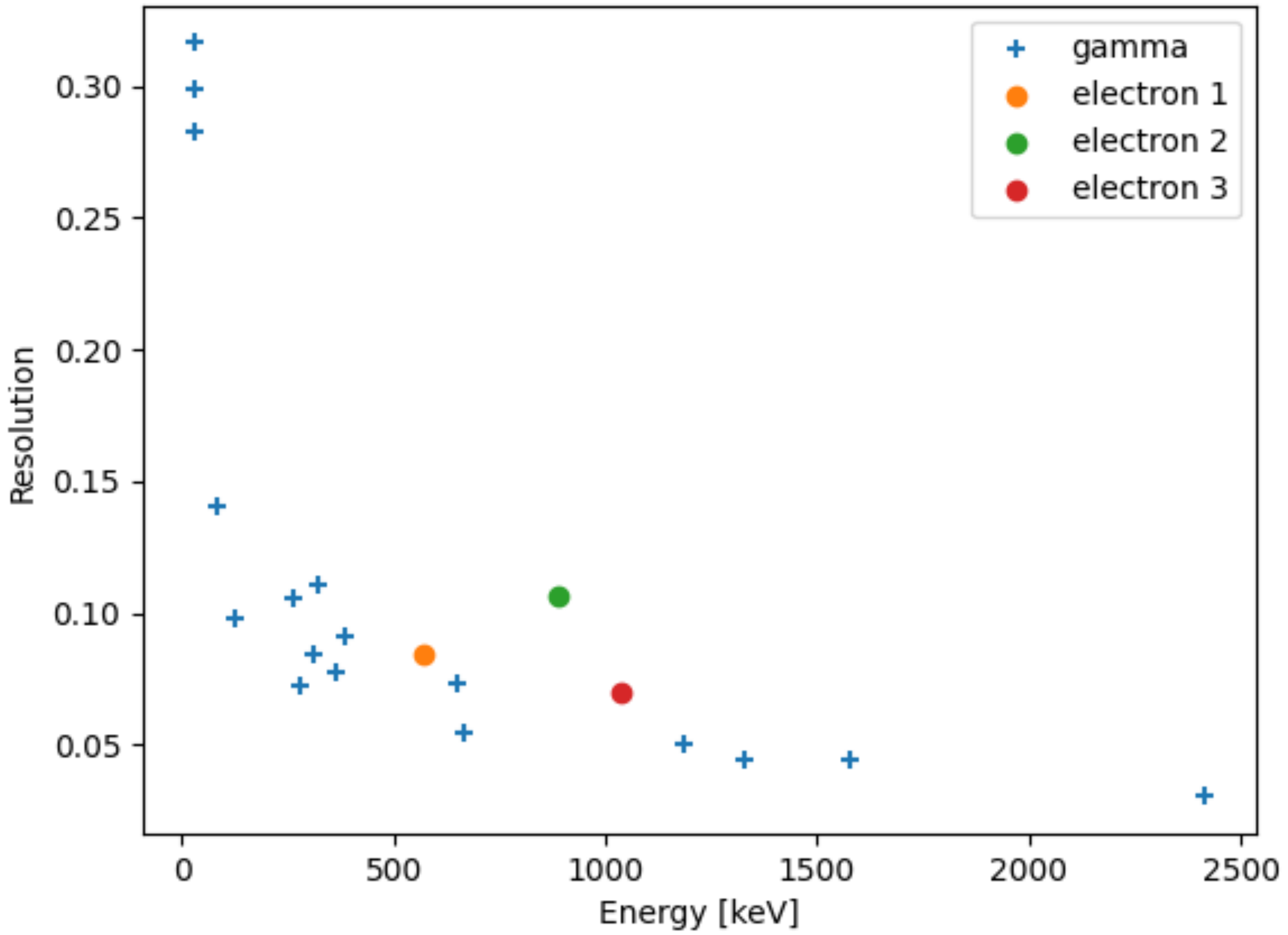
✗ Very high voltage

  - Filter with Helmholtz coil/permanent magnets (magnetic filed) ✓
  - Compton scattering ✗ Low flux & hard scatter detector control
- Intrinsic monochromatic beta source ✓
  - Internal conversion
  - E = (Ei - Ef) - EB

CsI scintillator performance study: Bi-207 source

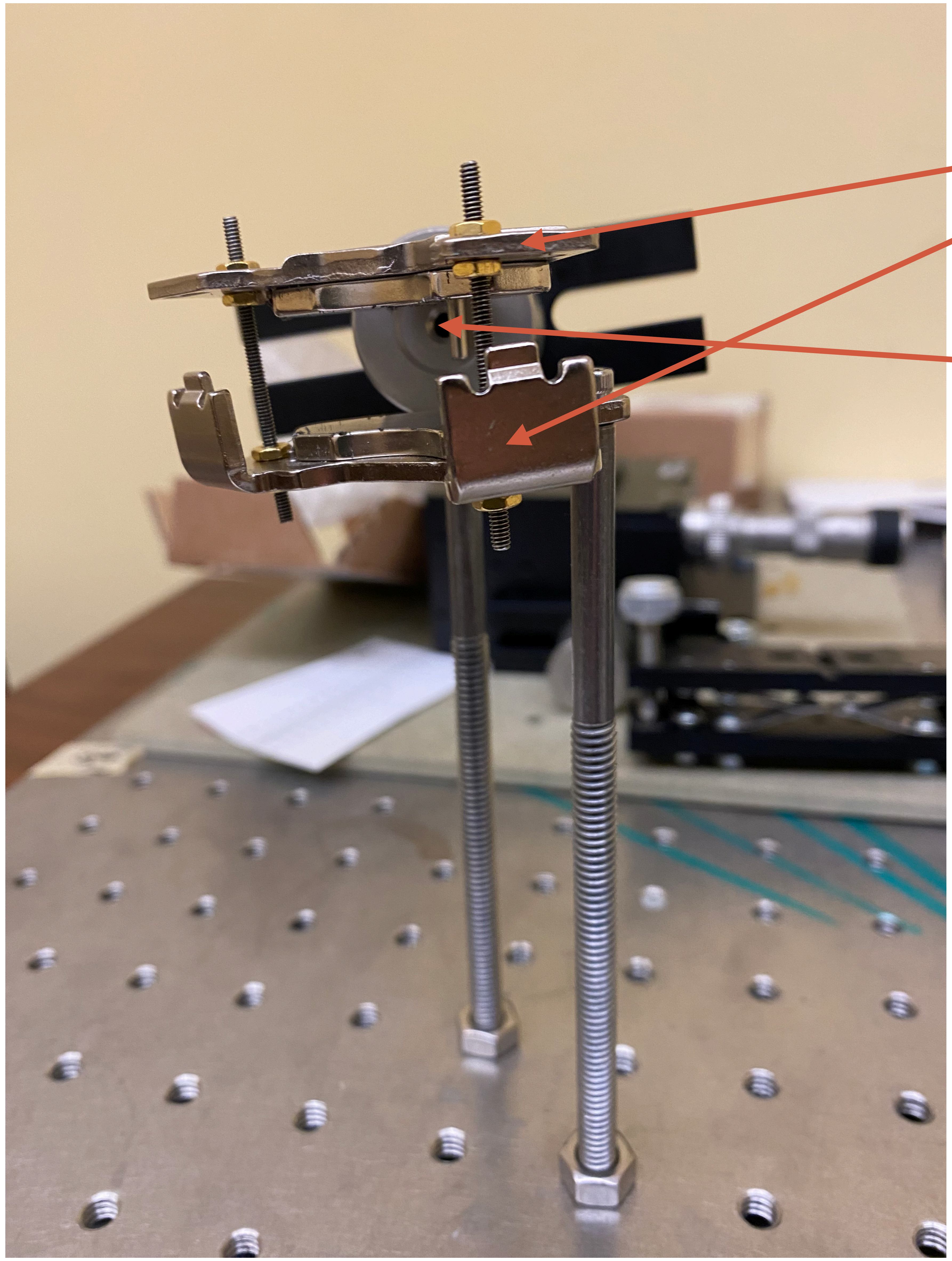






- 2-7% resolution for 500keV - 3MeV photon
- Accurate electron energy measurements, resolution compatible

CsI scintillator performance study: magnetic electron selector

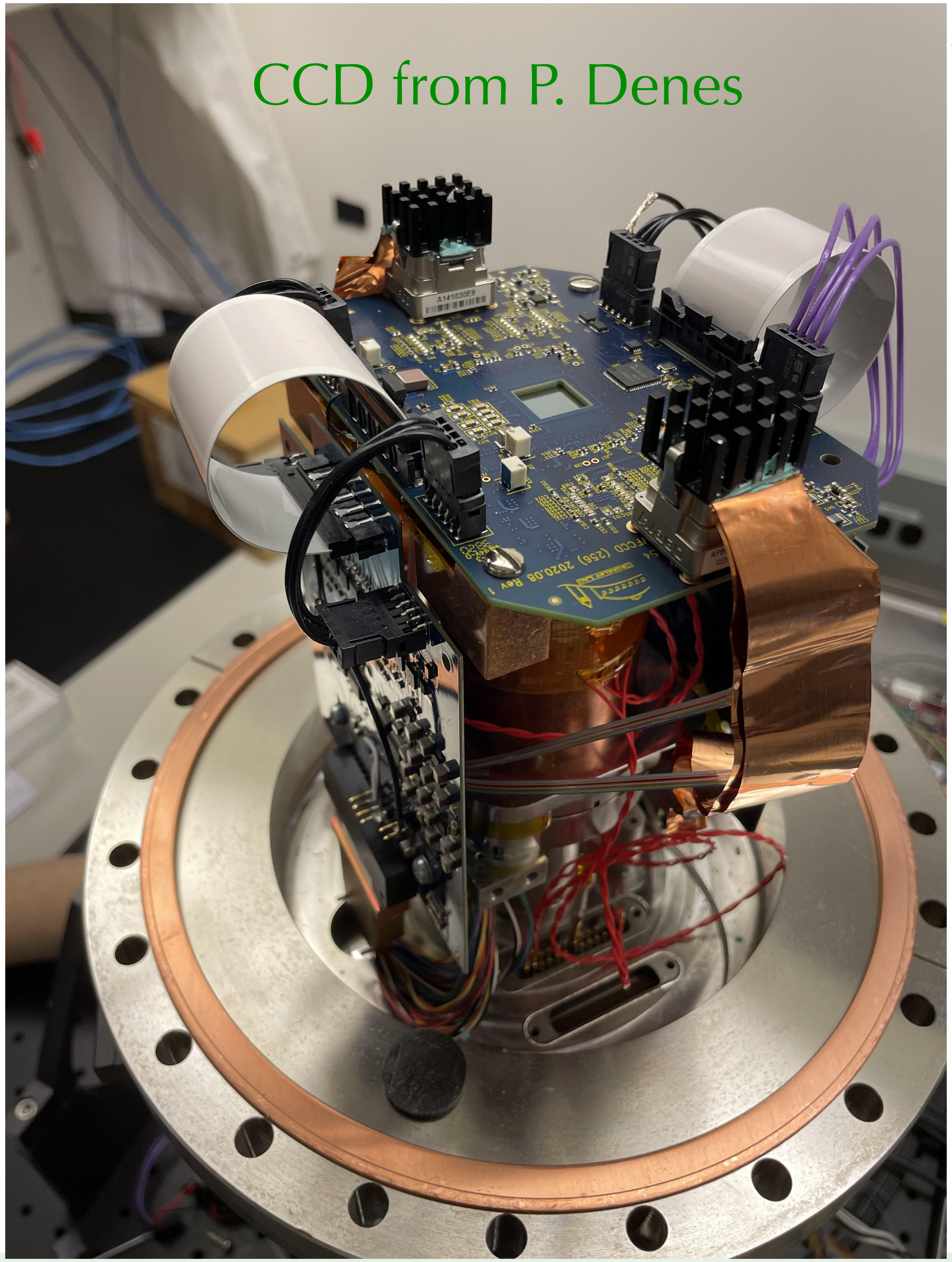


permanent magnets with adjustable separation distance (now 500 gauss)

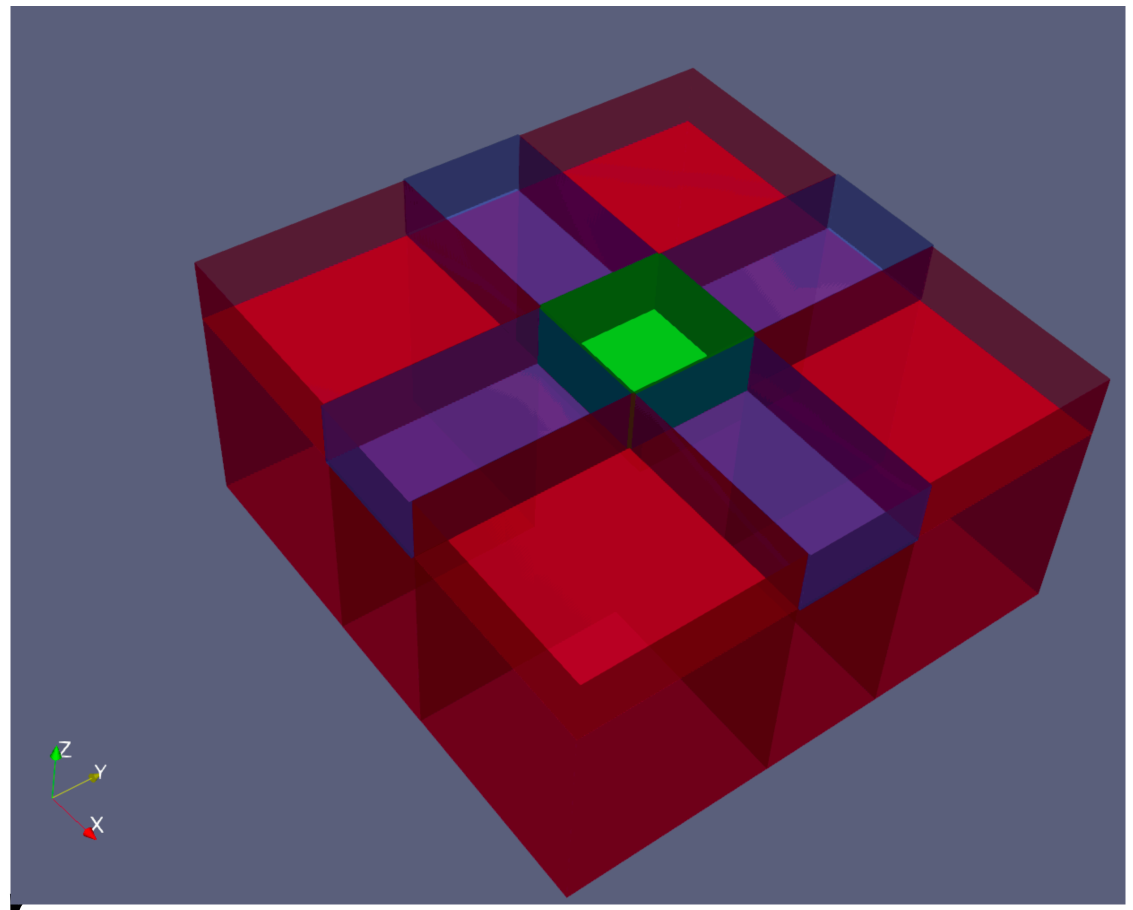
aperture to filter the desired electrons

- ~400 gauss magnetic field to bend 5cm-radius for a 1MeV electron
- Through adjust the aperture, able to produce electron beams with different energy to do a full-energy-spectrum scan

Pixel detector choices: Is CCD pixel + CsI scintillator the best?



- Current plan: CCD + scintillator
  - Difficult to achieve the desired architecture
  - Brem photons from electrons in the scintillator
  - Spatial res decreases then it gets thicker

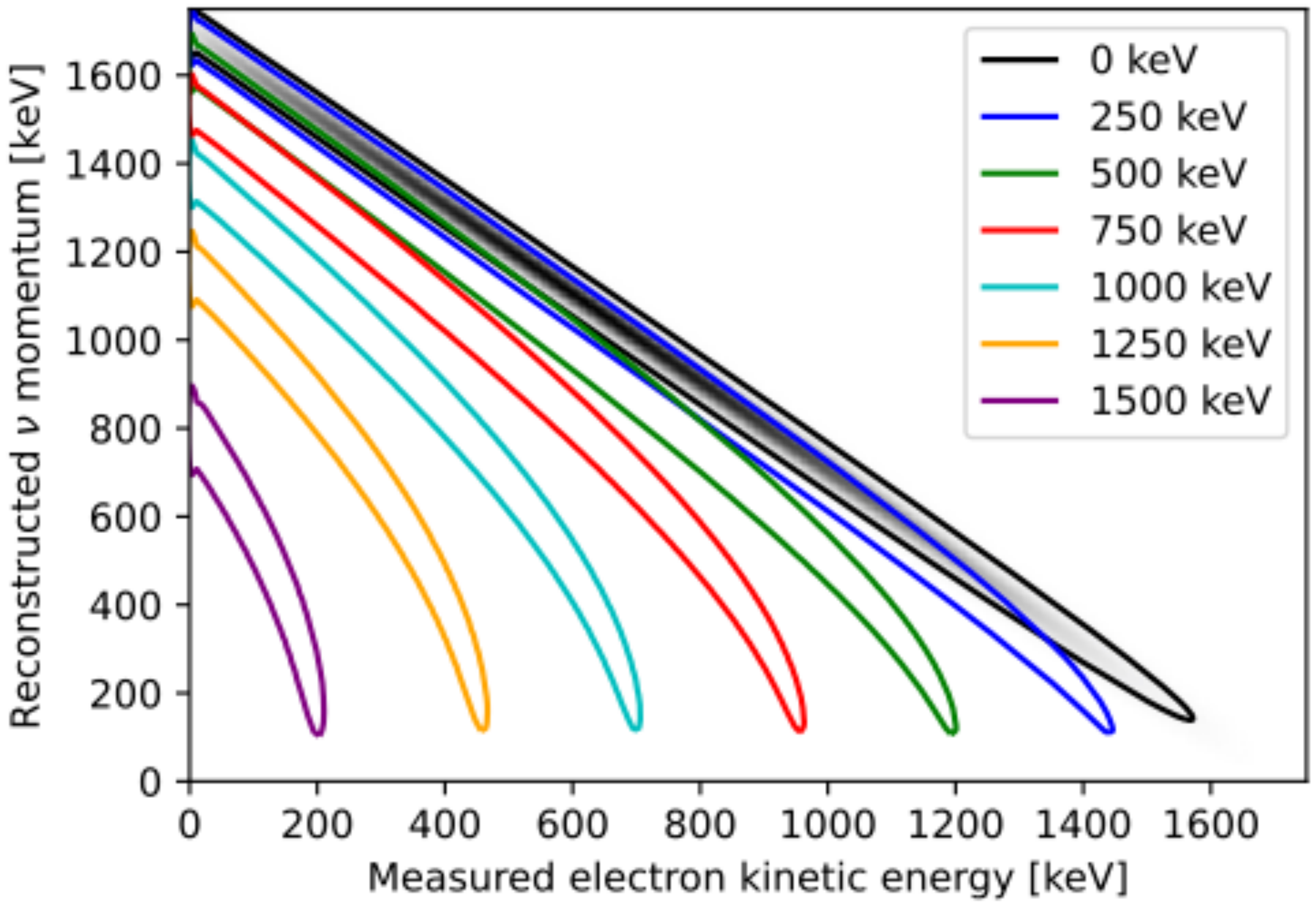


- Other considerations
  - CMOS + scintillator?
  - MAPS + scintillator?
  - Single piece structure to avoid using scintillator?

BACK UP

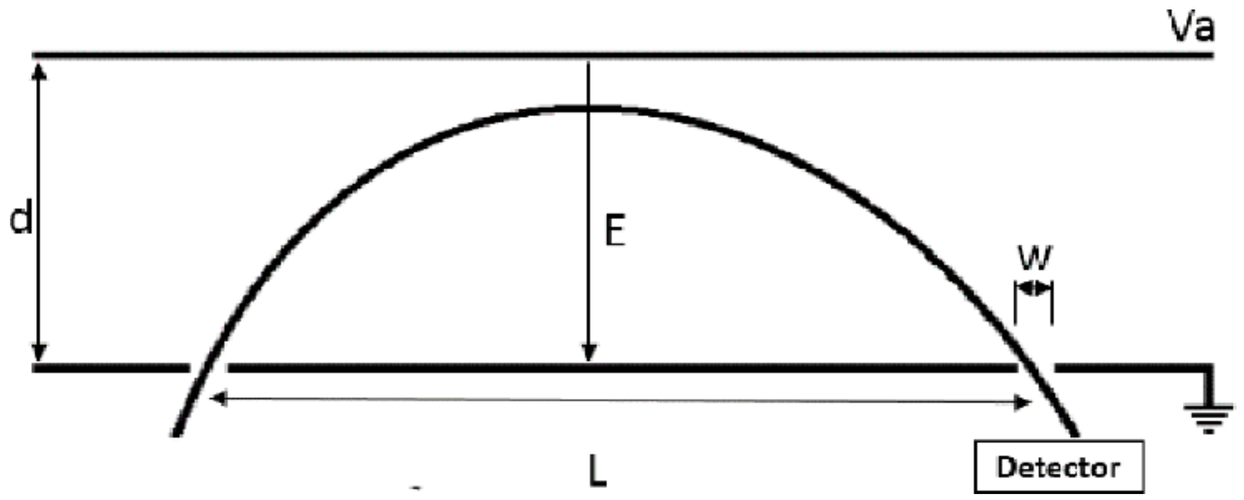
$$|\mathbf{p}_4| - |\mathbf{p}_i| = \sqrt{(Q - T_e)^2 - m_4^2} - (Q - T_e)$$

$$\sqrt{(Q - T_e)^2 - m_4^2}$$

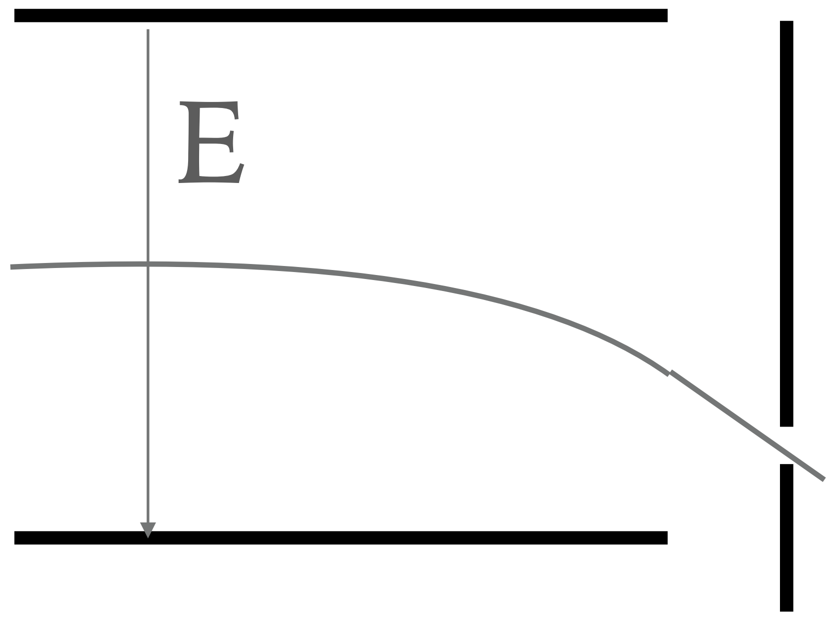


Te

CsI scintillator performance study: monochromatic beta source

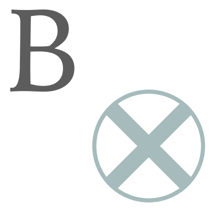


1e6 V needed



d = lV/4e6

l=0.5m, need 1kV to get 125 micron



200 gauss magnetic field to bend 10cm-radius

20A, 0.5cm radius, 50loops